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Lunar Surface Gas Turbine Power Systems With Fission Reactor Heat Sources

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Abstract

A concept for evolutionary development of lunar base nuclear power plants is proposed. Starting with a 20 kWe Closed Brayton Cycle system for an initial lunar outpost connecting multiple modular units to a single reactor for lunar bases, and the eventual deployment of multi-megawatt systems for lunar colonies is discussed. System performance and mass details were generated by an author developed code (BRMAPS) including options for increased power output by artificially depressing lunar daytime sink temperatures and maximum power generation during the lunar night.

Nomenclature

A_r	Radiating area, m^2
C_p	Working fluid specific heat, J/kg-K
d	Average sun-to-lunar orbit distance, $1.496*10^{11}$m
h_r	Gas heat transfer coefficient, W/m^2-K
L	Solar Luminosity (3.86×10^{26} W)
$\dot{m}$	Working fluid mass flow rate, kg/s
P_{IC}	Compressor Inlet Pressure, mPa
P_{OC}	Compressor Outlet Pressure, mPa
P_{IT}	Turbine Inlet Pressure, mPa
P_{OT}	Turbine Outlet Pressure, mPa
T_e, T_S	Equilibrium surface or space sink Temperature, K
T_{win}	Wall surface temperature at Radiator duct inlet, K
T_{wex}	Wall surface temperature at Radiator duct exit, K
α	Cycle temperature ratio
ε	Radiator surface emissivity
ε_R	Regenerator effectiveness
γ	Specific heat ratio of working fluid
η_b	Cycle heat input efficiency
η_c	Isentropic efficiency of compressor (function of polytropic efficiency, pressure ratio, γ)
η_t	Isentropic efficiency of turbine (function of polytropic efficiency, pressure ratio, γ)
σ	Stefan-Boltzmann constant (5.67×10^{8} W/m^2-K^4)

I. Introduction

Ever since the first lunar landing over 36 years ago, establishment of a permanent lunar presence by humans has been an intriguing concept. Establishment of initial lunar outposts which would gradually evolve into bases and eventually human colonies has been the topic of numerous studies (Refs. 1 to 4). Lunar bases and colonies would be strategic assets for development and testing of space technologies required for further exploration and colonization of favorable places in the solar system, such as Mars.

Specifically, the establishment of lunar mining, smelting and manufacturing operations for the production of oxygen, Helium 3 and metals from the high grade ores (breccias) of asteroid impact sites in the Highland regions would result in extraordinary economic benefits for a cis-lunar economy that may very likely exceed expectations. For example, projections based on lunar soil analyses show that average metal content mass percentage values for the highland regions is the following (Refs. 5 to 8): Al –13%, Mg – 5.5%, Ca – 10%, Fe – 6%. The iron content of the maria soil has been shown to reach 15 percent.

In time technologies culminating in effective utilization of these lunar resources would enable more ambitious projects such as construction of optical and radio astronomy facilities. Besides the tremendous benefits resulting from the absence of radio interference on the lunar far side, operation of a lunar radio telescope (RT) as an element of a "Very Large Baseline Array" (VLBA) could be integrated with an earth based telescope system. The separation distance of such a system would be some thirty times wider than the maximum possible separation of earth based telescopes. Since telescope resolving power is determined by the ratio of wavelength-to-baseline separation distance resolutions for the RT system at centimeter scale wavelengths would approach values of less then 10^{-5} arc seconds, thus permitting detailed observations on disks of nearby solar size stars (Ref. 9).

A key requirement for the establishment of permanent human presence on the lunar surface is a reliable power system to supply energy demands for life support, science, and operational requirements. Since such a power system is to provide continuous output through the 29.5 day synodic month, half of which receives no sunlight unless the power plant is located at the poles, the advantage of a heat source independent of the sun is obvious. Several studies have been performed using the lunar regolith soil as a thermal energy storage medium integrated with a solar power system. The conclusion reached (Ref. 10) was that while thermal energy could be stored as relatively low temperature sensible heat, high temperature latent heat storage necessary for a viable dynamic power system would require an elaborate heat distribution, storage, and retrieval network of such technological complexity that the concept was judged to be impractical.

To circumvent the energy storage problems associated with solar power, energy conversion systems using nuclear heat sources offer definite advantages for lunar power plants. In this report the authors discuss several conceptual lunar power plant designs utilizing CCGT (Closed Cycle Gas Turbine) power systems with nuclear reactor heat sources. Nominal power output ranges from 20 kWe for an initial outpost to power plants for lunar colonies, utilizing turbo-alternator engine modules of up to 30 MWe capacity. To facilitate the cycle heat rejection process a unique approach to lowering lunar daytime sink temperatures based on the analysis of Bien and Guentert (Ref. 11) using a light weight (~0.25 kg/m^2) aluminized plastic cover in the vicinity of the radiator is proposed. Conversely, during the lunar night when sink temperatures are very low, a method for generating excess power is also discussed.

In addition advanced space radiator technology, which utilizes light weight high thermal conductivity carbon-carbon composites or encapsulated "annealed pyrolytic graphite" (APG) structures with specific mass values approaching 1 kg/m^2, could contribute to achieving order of magnitude reductions of radiator mass values compared to current "state of art". This is especially significant for multi megawatt (MMWe) CCGT power systems for which radiator area requirements will be in the 10,000 m^2 range.

II. Lunar Temperature Environment during Synodic Month

The lunar environmental sink temperatures over the synodic month from full moon to the next full Moon (Ref. 8) are shown in Figure 1. Lunar midday temperatures can be computed from a relatively simple relationship based on the solar luminosity, and lunar surface emissivity and absorptivity to solar radiation as shown in Eq. (1)

$$T_e = \sqrt[4]{\left(\alpha / \varepsilon\right)\left(L / 4\pi\sigma d^2\right)} \tag{1}$$

It is understood that "full moon" as viewed from earth actually is lunar midday at a central longitude location on the side of the moon facing earth. A more detailed procedure which includes infrared radiation from Earth during the lunar night is given by Juhasz (Ref. 12), who obtained lunar night temperatures of 70 K. Regarding Figure 1, surface temperatures are seen to drop from about 385 K at noon to near 120 K at sunset, then to just over 80 K before sunrise. Temperatures then (in terms of lunar time) rapidly climb to the previously quoted noontime, or "full moon" values. A close examination of the temperature profile shows that lunar surface temperatures are at 360 K or above for about 28 percent of the synodic month, which is more than 8 earth days. Obviously, heat rejection to such high sink temperature levels would require very large radiator surface areas. Fortunately, as explained below, the sink temperature can be lowered by the use of an aluminized sheet of plastic, which can be spread out over the lunar surface in the vicinity of the radiator as proposed by Bien and Guentert (op. cit.) and illustrated in Figure 2. In this concept the vertically oriented radiator wings, emanating on both sides of a centrally located vehicle, which contains the nuclear reactor/shield heat source and the gas turbine power system, are aligned in the lunar equatorial plane thus ensuring that negligible solar radiation is incident on the radiator, because the inclination of the mean lunar equator to the ecliptic is only ~1.6°. Even if the outpost or base were to be located not at the lunar equator, but within a latitude range of ±30°, the lowering of sink temperature and corresponding radiator reduction could still be achieved by tilting the radiator relative to the local vertical at an angle equal to the local latitude. Of course the direction of tilt would be towards the lunar equator.

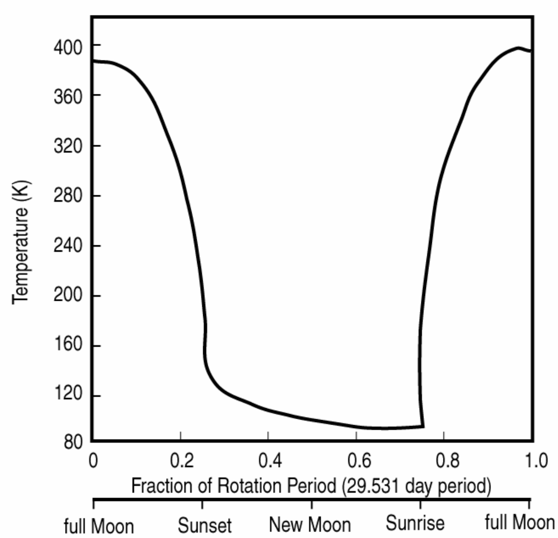

Figure 1.—Lunar surface temperatures variation—Noon to Noon (Ref. 8).

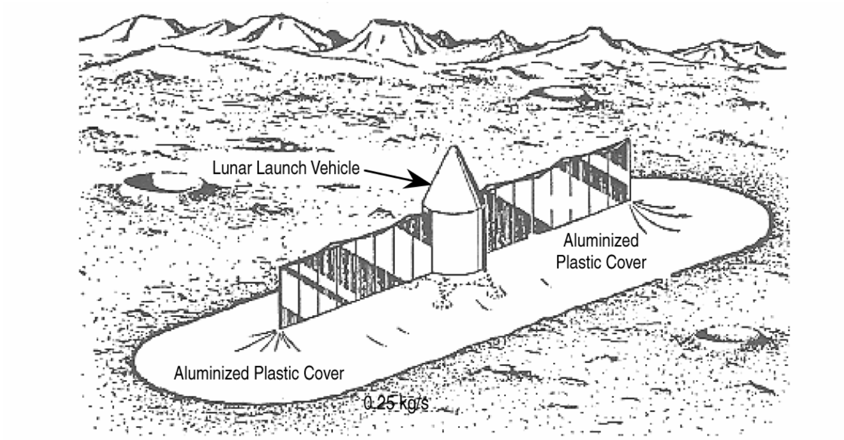

Figure 2.—Power system radiator and reflective cover on Moon (Bien and Guentert) (Ref. 11).

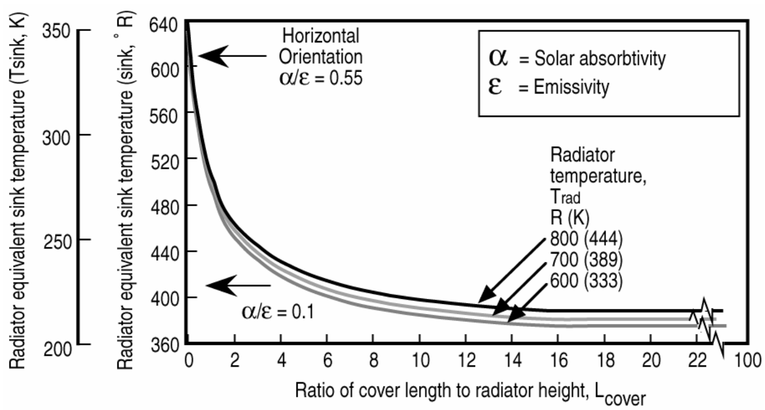

Figure 3.—Effect of cover length and radiator temperature on equivalent sink temperature (Bien and Guentert) (Ref. 11).

As will be shown in section IV.B of this paper, placing the reactor below ground level for permanent power plant installations will permit the lunar soil to provide some of the neutron and gamma shielding requirement for the energy conversion and radiator sub-systems. In addition, an exclusion zone of up to 2 km radial distance from the reactor is advisable for human crew personnel. Maintenance and repairs within the exclusion zone will need to be carried out by remotely controlled devices or autonomous robots.

The aluminized sheet mentioned above, having a low solar absorptivity (near 0.12), would replace the high lunar surface absorptivity, α, in the vicinity of the radiator which may be as high as 0.9.

It is this high solar absorptivity which leads to the high lunar day sink temperatures for a vertical radiator when the sun is directly overhead. Based on the mathematical analysis of re-radiating and reflecting surfaces a chart as shown in Figure 3 was constructed (Ref. 11). Use of this chart allows accurate estimation of sink temperature as a function of “cover length-to-radiator height” ratio with radiator temperature as a parameter.

Note that the lowest of the three radiator temperatures, namely 333 K, would be impossible without the cover, since the sink temperature is already at 334 K. Figure 3 also shows that for a radiator height of 1 meter a cover with about 6 meters on each side would be sufficient to lower daytime sink temperatures to no more than 230 K.

The reference value of ~340 K for a horizontal radiator with $\alpha/\varepsilon = 0.55$ was confirmed by the TSCALC code (Ref. 12) to agree with the previously given value (Ref. 3). Use of this code showed that the minimum lunar night sink temperatures would drop to 70 K.

III. Closed Cycle Gas Turbine (CCGT) Power System Conceptual Designs

As envisioned for purposes of this study, lunar power plants with nuclear reactor heat sources will likely evolve from an early power output capability to meet the needs of a lunar outpost manned by three to four astronauts to lunar bases and eventual colonies with human crews of several thousand. Consequently power plant output would need to grow from about 20 kWe to multi megawatt levels. For this study, a CCGT system of 20 kWe output power level was arbitrarily selected for lunar day operation. Using the author generated BRMAPS code, a preliminary conceptual preliminary design of a lunar power plant was laid out by replacing the SP-100 thermoelectric conversion system with a CBC, as suggested in Figure 4. It should be understood that this study represents the first step in a number of design iterations before final detailed design is arrived at.

A. Initial Operating Capability (IOC) With 20 kWe Output

For purposes of this study a CCGT power system which is based on the "Closed Brayton Cycle" (CBC) was assumed. System analysis and mass optimization studies were carried out using the numerical code referred to above. Radial compressor and turbine technology is particularly suited to the cycle pressure ratio requirement of near 2.0. Gas foil bearings at both ends of the alternator, cooled by compressor exit bleed flow were assumed for supporting radial loads. Not shown is a gas foil thrust bearing. As mentioned above, a CBC power system schematic including state points is shown in Figure 4. The heat source would utilize SP-100 technology (Buden, Ref. 13), and the heat rejection subsystem features lightweight C-C heat pipe radiator technology as demonstrated by Juhasz and Bloomfield (Ref. 3) (op. cit.). The 42 m^2 total two sided radiator area was computed assuming an average lunar day sink temperature of 360 K and an alternator power output of 20 kWe. At a computed average thermodynamic efficiency of ~32 percent, approximately 65 kWt of reactor thermal power would be required, assuming a well insulated heat source (>95 percent reactor thermal power sent to CBC).

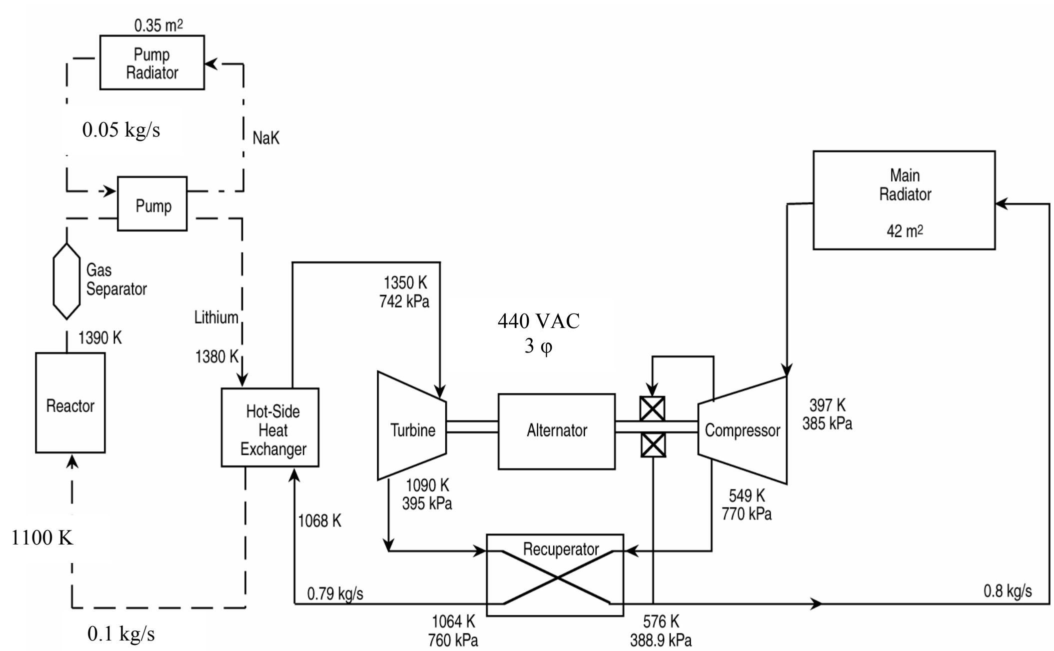

Figure 4.—Baseline schematic for 20 kWe CBC power system.

B. Mathematical Analysis of Closed Brayton Cycle

The analysis of the conceptual power system was carried out using an author generated computer code (Juhasz, Ref. 14) referred to as BRMAPS. This code contains a key sub-routine which performs a triple objective non-linear optimization procedure using generalized reduced gradient techniques to identify the three cycle operating conditions at which maximum thermodynamic efficiency, minimum radiator area, and minimum system mass are obtained. Salient theoretical expressions derived for determining the needed objective functions are given below:

(1) ***Thermodynamic Cycle Efficiency*** **(η_{th})**

With cycle efficiency defined as the net work output, i.e., the difference between turbine work and compressor work, divided by the cycle input thermal energy, the author derived the expression given in Eq. (2) for the CBC thermodynamic efficiency, η_{th}.

$$\eta_{th} = \frac{\eta_b \left(\frac{\Theta_T - 1}{\Theta_C}\right)\left(\alpha\,\eta_t - \frac{\Theta_C}{\eta_C}\right)}{\alpha\left(1-\varepsilon_R\right)+\varepsilon_R\,\eta_t\,\alpha\left(1-\frac{1}{\Theta_T}\right)+\varepsilon_R - 1 + \frac{1}{\eta_C}\left(1-\Theta_C + \Theta_C\,\varepsilon_R - \varepsilon_R\right)} \tag{2}$$

where

$$\Theta_C = (P_{OC} / P_{IC})^{(\gamma-1)/\gamma} \text{ is the compressor pressure ratio parameter} \tag{3}$$

and

$$\Theta_T = (P_{IT} / P_{OT})^{(\gamma-1)/\gamma} \text{ is the turbine pressure ratio parameter} \tag{4}$$

Note that due to cycle pressure loss the "loss pressure ratio," $(P_{IT} / P_{OT})/ (P_{OC} / P_{IC})$ ~0.94 for a regenerated cycle with ε_R = 0.95. For a non-regenerated cycle the ratio is in the 0.98 range.

(2) ***Radiating Area***

Similarly, an analysis of gas turbine working fluid being cooled in a radiator duct led to the following expression for radiating area required for a CBC space power system (Ref. 14).

$$A_r = \dot{m}\cdot C_p \cdot\left[\frac{1}{h_r}\cdot\ln\left(\frac{T_{win}{}^4 - T_s^4}{T_{wex}{}^4 - T_s^4}\right)+\frac{1}{\left(4\cdot\sigma\cdot\varepsilon\cdot T_s^3\right)}\cdot\left[\ln\frac{\left(T_{win}-T_s\right)\cdot\left(T_{wex}+T_s\right)}{\left(T_{wex}-T_s\right)\cdot\left(T_{win}+T_s\right)} - 2\cdot\left(\tan^{-1}\cdot\frac{T_{win}}{T_s} - \tan^{-1}\cdot\frac{T_{wex}}{T_s}\right)\right]\right] \tag{5}$$

Note that the actual radiator sail area depends on the view factor to the space background. Thus a flat plate surface radiating from both sides (view factor = 2) would have a sail area value equal to half that determined by Eq. (5). To allow for heat pipes damaged by micrometeoroids over mission life the vale for A_r was incremented by 25 percent.

(3) ***Power System Mass***

The individual masses for key sub-systems and components shown in Figure 4 were determined by use of empirical mass models, taking into account certain theoretically derived parameters such as working fluid mass flow rate, thermal power, fluid temperatures, and transport properties. Overall system mass then became the sum of component masses. The cycle working fluid was a 40/60 mol% He/Xe inert gas mixture having an equivalent molecular weight of 80. The working fluid is heated to 1350 K turbine inlet temperature by a liquid lithium-to-gas heat exchanger as shown. For the conditions shown the rotor speed was computed at 36,000 rpm. Cycle state points were computed for the minimum mass pressure ratios (near 2.0), assuming an average isentropic efficiency of 0.85 for both, the compressor and turbine. The alternator is located on the same shaft with the compressor and turbine and it generates 3 φ, 440 VAC current at 1200 Hz, using three pole pairs. Due to this higher frequency the mass of electrical components is significantly lower than for conventional power at 60 Hz. A detailed component mass breakdown for the reference system is shown in Table 1.

TABLE 1.—20 kWe BRAYTON SYSTEM COMPONENT MASSES BREAKDOWN

Component	Component mass (kg)	Component mass (Percent of mass)
Reactor	364	22.1
Instrument shield	315	19.1
Source heat exchanger and pump (pump)	210 (40)	12.7
Recuperator	100	6.1
Turbo-alternator	60	3.6
Instrumentation and controls	80	4.9
Main radiator	210	12.7
Auxiliary radiators	66	4.0
Radiator HX, ducting, misc., structure	240	14.8
Total system mass	1,650	100

C. Power Modulation Options at Various Operating Conditions

The base load power output can be enhanced due to variation of the equilibrium sink temperature by

(1) Use of the aluminized reflective cover during the lunar day resulting in T_e = 230 K
(2) Natural drop of lunar night equilibrium sink temperature to T_e = 70 K

Using these strategies it can be shown that the fixed radiator area of 42 m^2 will be sufficient to radiate a greater amount of non-convertible cycle reject heat to the equilibrium sink temperature. To generate the higher output power level using the same turbo-alternator, the operating pressure level is increased by infusion of additional working fluid from a high pressure storage cylinder, referred to as an accumulator, into the compressor flow stream. The working fluid mass flowrate and the operating pressure level will also increase proportionately, but state temperatures and rotational speed will remain constant. The increased shaft power transmitted to the alternator driven load results from increased alternator current flow at constant terminal voltage. The higher electric power output at constant thermal-to-electric conversion efficiency necessitates a proportional increase in reactor thermal power output. This is accomplished by rotating the reactor control drums so that a higher number of neutrons are reflected back into the core, thus increasing the number of U_{235} neutrons undergoing fission. Simultaneously increasing the reactor heat source thermal power output will yield the increased electric power output with all state temperatures being the same as during the base load operation.

Of course these operations will need to be reversed at the end of the lunar night. Reactor thermal power will need to be reduced by control drum control causing excess neutrons to be absorbed from rather than reflected, and cycle working fluid will have to be transferred back into the accumulator using a small electric motor driven charging compressor. Note that the accumulator and the small charging compressor masses are included in the last row of Table 1.

A comparison between the base load and the modulated power operating conditions is shown in Table 2.

TABLE 2.—LUNAR POWER GENERATION OPERATING CONDITIONS (20 kWe BASE LOAD)

Gas turbine cycle parameters (Regenerated cycle – ε_{RG} = 0.95)	Lunar day	Lunar day with aluminized cover	Lunar night
Turbine inlet temperature, K	1350	1350	1350
Equilibrium sink temperature, K	360	230	70
Compressor inlet temperature, K	397	397	397
Compressor outlet temperature, K	549	549	549
Reactor inlet temperature, K	1068	1068	1068
Output power level, kWe	20	32	35
Thermal input power, kWt	63	100	110
Turbine inlet pressure, MPa	0.74	1.18	1.30
Working fluid mass flow rate, kg/sec	0.8	1.28	1.4
Rotor speed, rpm	36,000	36,000	36,000
Cycle temperature ratio	3.4	3.4	3.4
Cycle pressure ratio	2.0	2.0	2.0
Cycle thermal efficiency, percent	32	32	32
Main radiator area, m^2	42	42	42

IV. Multi-Megawatt Power Systems

As indicated in the "Introduction" section of this paper, the authors suggest that initial lunar outposts are likely to evolve into permanent bases and eventually into colonies. Such evolutionary development will require a parallel growth in the generation of lunar surface power from the multikilowatt to the multi-megawatt (MMW) range. Assuming that the advance in high temperature materials technology (i.e., refractory metals and ceramics) will enable CCGT turbine inlet temperatures in the 1500 K range, a simple (non-regenerated) CBC cycle utilizing HTGR (high temperature gas reactor) technology is proposed as shown in the simplified schematic featured in Figure 5. The concept utilizes multi stage axial compressor and turbine technology adapted from aircraft engine or stationary power generating applications, but modified for pure He working fluid. Note that this non-regenerated cycle uses direct heating of the helium working fluid by a gas reactor and the heat rejection at the low temperature side of the schematic would be accomplished by passing the He working fluid directly over heat pipe evaporators which protrude into the flow passage of the radiator duct (The condenser sections of the heat pipes thermally communicate with high conductivity and emissivity radiating surfaces for the final step in the space heat rejection process.). An important feature illustrated by the cycle schematic is the complete absence of any heat exchangers. This should lead to lower overall system mass and cost and to higher reliability due to the smaller number of series connected components, whose system reliability will be the product of its series connected components. Of course the price for this simplicity would be lower thermodynamic cycle efficiency. Considering that polytropic efficiencies of 0.9 have been achieved for axial compressors as compared to ~0.8 for radial compressors, this penalty can be ameliorated to some degree by the higher compressor and turbine efficiencies achieved by axial turbo-machinery. While the improvement in turbine polytropic efficiencies is from ~0.9 to 0.92 between radial and axial machines the effect on cycle efficiency, radiator area, and system mass is positive for each of these parameters.

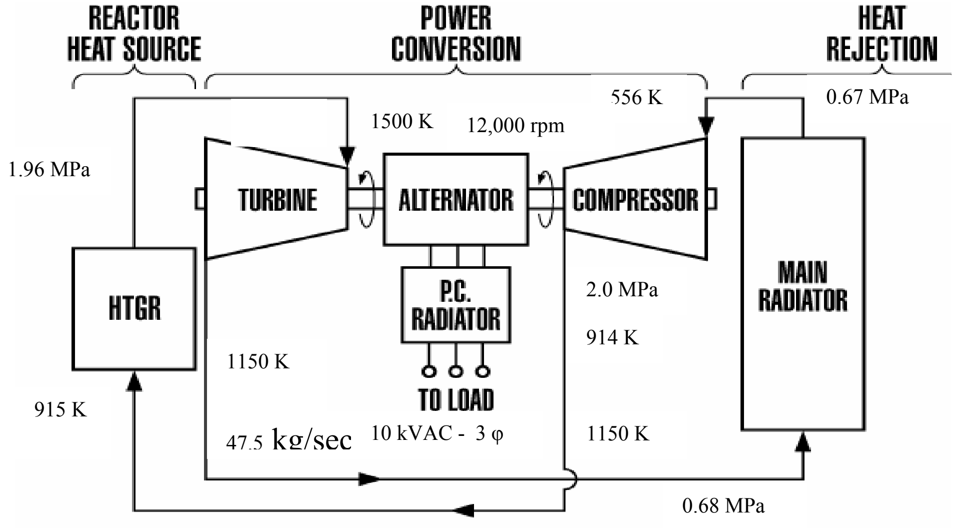

Figure 5.—Simplified baseline schematic for a 30 MWe Lunar Helium CBC power plant.

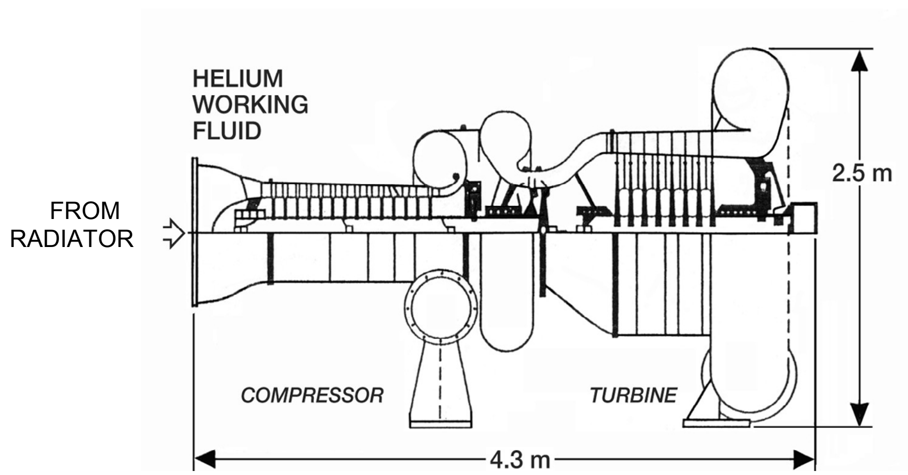

Figure 6.—30 MWe Helium turbo-compressor (TC).

A. Helium Turbo-Compressor for 30 MWe Output

The design for a helium turbo-compressor rotor shown in Figure 6, capable of supplying shaft power to a 30 MWe alternator was derived by the author from a diagram for a 40,000 HP ground power machine using air working fluid in the compressor, and a mixture of air and combustion products of a hydrocarbon fuel as the working fluid for the turbine.

Rotor dimensions and operational details are given in Table 3 and the system mass distribution for major components and the overall turbo-compressor system mass is shown in Table 4. The change of the working fluid molecular weight from 29 for air to 4 for He required that the flow passage area be decreased with an increase in the design speed and the number of axial stages in both the compressor and turbine. Note that a separate study focusing on the alternator armature rotor dynamics, including radial bearing suspension for a 1/6 G lunar environment will need to be conducted at a future date. Nevertheless the turbo-compressor of this study is sized to drive an alternator (not shown) at 30 MWe terminal output. The alternator could be mounted on an adjacent platform and connected to the turbine shaft by a coupling.

TABLE 3.—PARAMETERS OF 30 kWe HELIUM TURBO-COMPRESSOR (TC) TO BE COUPLED WITH A 3-PHASE 6 POLE AC (600 HZ) ALTERNATOR

Parameter	Compressor	Turbine
Average hub radius, m	0.14	0.28
Casing diameter, m	0.36	0.77
Axial stages	14	8
Length, m	0.94	0.36
Design rotor speed, rpm	12,000	
Total rotor shaft length, m	1.9	
He mass flow rate, kg/sec	47.5	
Compressor pressure ratio[1]	3.0	
Max. operating pressure, MPa	2.1	
Turbine inlet temperature, K	1,500	

[1]Non-regenerated cycle.

TABLE 4.—30 kWe BRAYTON SYSTEM COMPONENT MASS BREAKDOWN

Component	Component mass (kg)	Component mass (Percent of mass)
Reactor	26,800	26.3
Instrument shield	4250 (1 km excl.)	4.2
Source heat exchanger and pump	0	0
Recuperator	0	0
Turbo-alternator	15,780	15.5
Instrumentation and controls	3000	2.9
Main radiator	41,000	40.3
Auxiliary radiators	1840	1.8
Radiator HX, ducting, misc., and structure	9300	9.0
Total system mass	102,000	100

With the rotor design speed of 12, 000 rpm, the frequency of the generated 3 phase AC current will be 600 Hz for a six pole alternator. Alternator terminal voltage could be 10 kVAC.

B. Rotordynamic Modeling of Helium Turbo-Compressor Supported on Active Magnetic Bearings

Active magnetic bearings (AMBs) provide advantages over conventional bearing systems for applications such as a 30 MWe CCGT system rotor support, including improved vibration and stability performance and greatly extended bearing service life. Magnetic bearings are well suited to operate at elevated temperatures and high altitudes. Provenza et al. (Ref. 15). demonstrated operation of AMB at temperatures exceeding 800 K. Combining AMBs with innovative structural design and advanced materials creates potential to achieve great operational performance in future CCGT planetary surface power plants.

A crude finite element model of a magnetic bearing rotor was constructed. The major components of this rotor system are shown schematically in Figure 7. Preliminary rotordynamic analysis was performed using an isotropic radial bearing stiffness of 17.5267×10^6 N/m (100,000 lb/in) at each radial bearing. The first four whirl frequency pairs have been plotted on a Campbell diagram in Figure 8. The upper line in

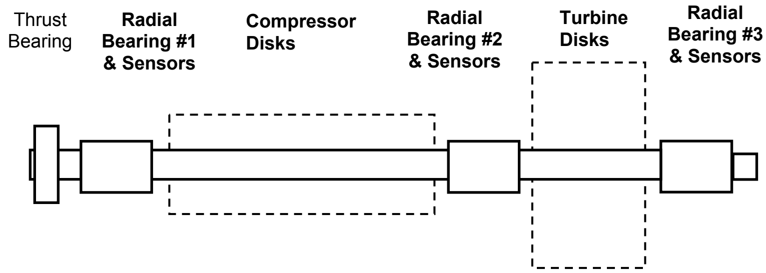

Figure 7.—Rotor components and sensor/actuator locations.

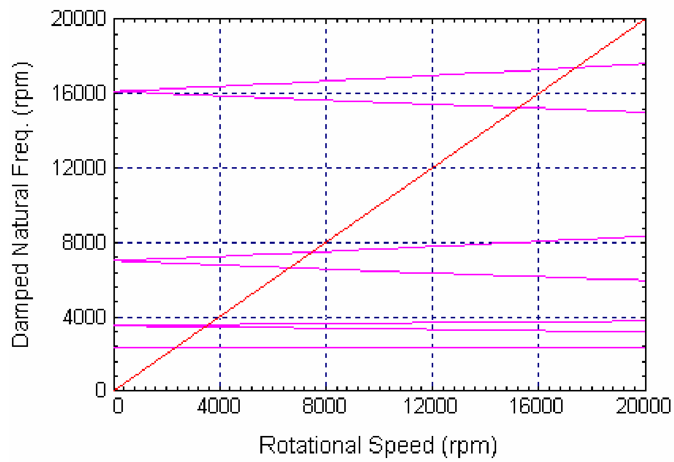

Figure 8.—Rotor Campbell diagram.

TABLE 4.—FORWARD WHIRL CRITICAL SPEEDS

Mode number	Speed, rpm
1	2,366
2	3,612
3	7,560
4	17,454

each whirl speed pair indicates forward whirl, while the lower is a backward whirl. The intersections between the synchronous excitation line and damped natural frequencies indicate synchronous whirl conditions. Note that the design speed of 12,000 rpm is in a stable region between the third and fourth mode critical speeds. The forward whirl critical speeds are listed in Table 4.

The actual magnetic bearing stiffness will change with frequency. Therefore, critical speeds for various stiffness rates of the bearings were calculated. The resultant critical speeds versus bearing stiffness are illustrated in Figure 9. It can be noted that no critical speed is encountered for the operating speed of turbo-compressor rotor for bearing stiffness up to 175.267×10^6 N/m (1×10^6 lb/in).

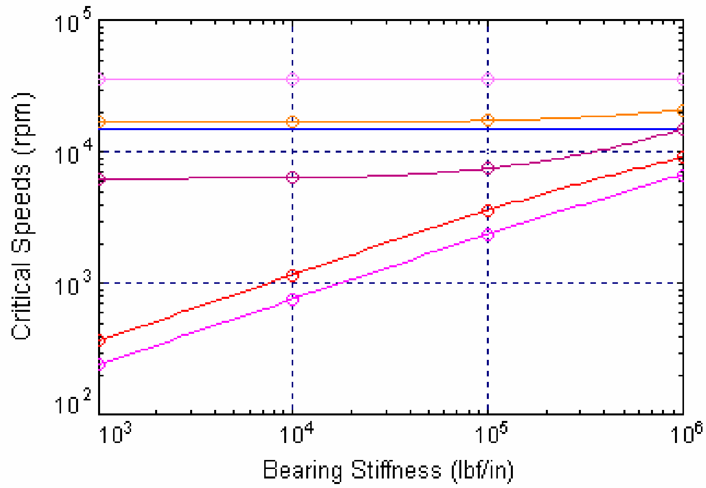

Figure 9.—Rotor critical speed map.

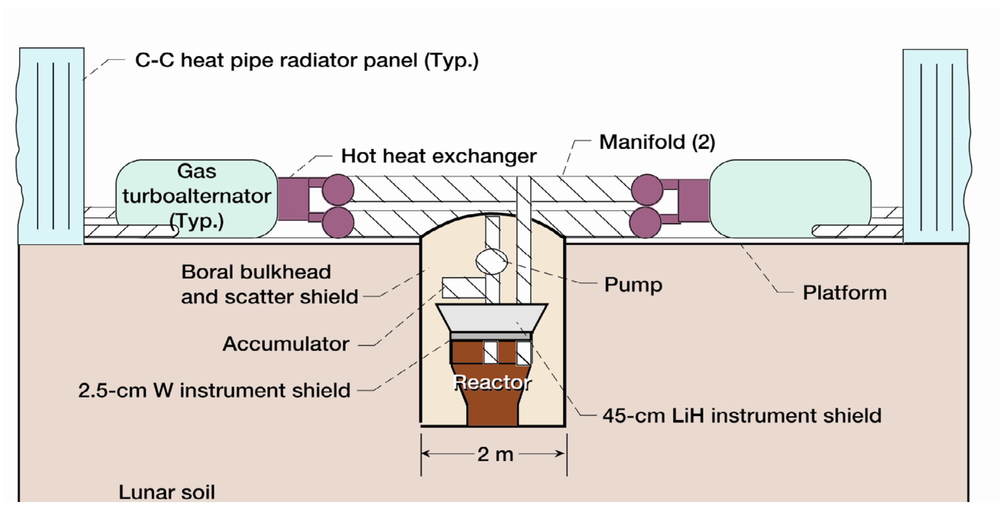

Figure 10.—Section showing subsurface reactor installation supplying thermal input to dual gas turbines each equipped with a heat pipe radiator (Ref. 3).

C. Multi-Megawatt Power Modulation Options

As already discussed in section III.C, the base load power output could be enhanced by taking advantage of variations of the lunar equilibrium sink temperature in the immediate vicinity of the vertically oriented heat rejection radiator surfaces. With the reactor and conical frustum shield buried below the surface as shown in Figure 10, dual turbo-alternator sets can be thermally integrated with a single reactor in a manner such that their vertically oriented radiators are in single plane so that the surfaces do not "see" each other.

Unfortunately this arrangement may not be possible for multi-megawatt turbo-alternator/radiator configurations. This is illustrated in Table 5, which shows salient operating parameters during the lunar day-night cycle. As for the operating conditions of the 20 kWe base-load power system shown in Table 2, the increased power generation capability with the same turbo-alternator and radiator is possible for the MMW case. The problem is that for a 30 MWe CBC power system the 7,800 m^2 radiator sail area would require a radiator configuration which for a 5 m height would be 1560 m long. To reduce this length one

TABLE 5.—LUNAR POWER GENERATION OPERATING CONDITIONS (30 MWE BASE LOAD)

Gas turbine cycle parameters (Non-regenerated cycle)	Lunar day	Lunar day with aluminized cover	Lunar night
Turbine inlet temperature, K	1,500	1,500	1500
Equilibrium sink temperature, K	360	230	70
Compressor inlet temperature, K	556	556	556
Compressor outlet temperature, K	913	914	914
Reactor inlet temperature, K	913	914	914
Output power level, MWe	30	32.5	33
Thermal input power, MWt	143	155	157
Turbine inlet pressure, MPa	2.0	2.16	2.2
Working fluid mass flow rate, kg/sec	47.5	51.4	52.2
Rotor speed, rpm	12,000	12,000	12,000
Cycle temperature ratio	2.7	2.7	2.7
Cycle pressure ratio	3.0	3.0	3.0
Cycle thermal efficiency, percent	21	21	21
Main radiator area, m^2	15,600	15,600	15,600
Radiator sail area, m^2	7,800	7,800	7,800

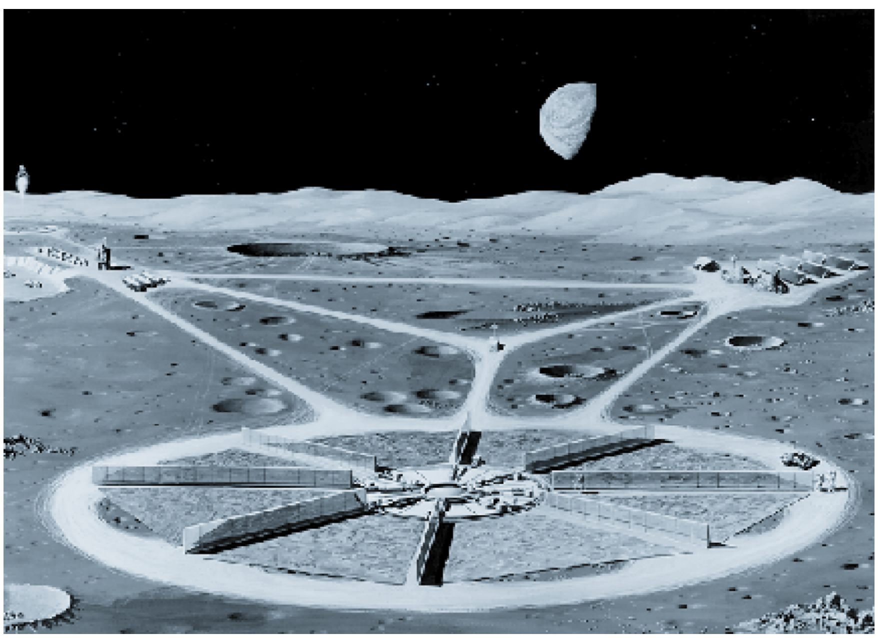

Figure 11.—Artist rendering of a Lunar nuclear CBC power plant with a "wheel spoke" radiator configuration (Ref. 3).

could resort to a "wheel spoke" configuration with the vertical radiator panels emanating from a central hub containing the reactor and power system like wheel spokes with even angle spacing, as shown in Figure 11.

But since the panels would now be able to radiate to each other there would be a penalty on additional radiator required. This penalty would increase as the angular spacing decreased. Thus, for a four spoke (90°, also referred to as a "cruciform" geometry the radiator area would have to be increased by ~25 percent to compensate for the radiative interchange between two panels. For a six spoke arrangement the penalty would be over 40 percent and even higher for the eight spoke. But the length of panels would be closer to 400 m for the six spoke geometry with the radiator mass increased by 1.4 over the value listed in Table 4.

Another solution of the radiator area problem is to limit power generator modules to ~5 MWe with two “in-plane” turbo-alternator modules per heat source as indicated in Figure 10, thus giving 10 MWe output for each power plant. Conceptual design details for such power plants could be a topic for a future paper.

Conclusions

An evolutionary approach to establishing lunar base nuclear gas turbine power plants is proposed by the authors. Starting with a 20 kWe plant with a scaled down SP-100- type reactor heat source, it is shown on the basis of an author developed Brayton cycle analysis code that by resorting to working fluid (He/Xe) inventory management, additional power could be developed during the lunar day if a highly reflective aluminized plastic foil is deployed on the lunar surface in the immediate vicinity of the vertically mounted radiator. Carrying inventory control one step further power output could be increased to 35 kWe by taking advantage of the low sink temperature during the lunar night. Combining several of such Brayton cycle turbo-alternators in a parallel configuration to the same reactor heat source can boost output power to 100s of kWe as the early lunar outposts evolve into permanent bases. For permanent lunar colonies capable of supporting several hundred humans engaged in lunar mining and manufacturing activities a power generation concept comprising a number of multi- megawatt power plants is proposed. Terrestrial power grids containing a number of power generating sources could serve as a model for an integrated lunar power system, especially concerning proven techniques of synchronizing the three phase AC power output of several power plants. Power distribution to various loads could be accomplished using copper, or aluminum alloy wiring for the IOC configuration. However, as HTS (high temperature superconducting) technology is further developed, appropriate utilization of this technology based on either YBCO (yttrium-barium-cobalt) or BSCO (barium-strontium-cobalt) could lead to significant reductions in transmission line mass.

Preliminary design for a typical 30 MWe helium turbo-compressor including rotor-dynamic analysis shows that there is a wide stable operating area at 12,000 rpm between the third and fourth critical speeds. The main problem for a power plant utilizing a single turbo-alternator of 30 megawatt capacity is the size of the radiator. One solution is to limit individual power plants to 10 MWe capacity provided by two high efficiency 5 MWe turbo-alternators each of which would require a radiator with a sail area of about 1500 m^2. At 5 m radiator height the length would be reduced to ~300 m in lieu of ~1600 m for a 30 MWe unit. Conceptual design for such power plants including could be a topic for a future paper.

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13. ABSTRACT *(Maximum 200 words)*

A concept for evolutionary development of lunar base nuclear power plants is proposed. Starting with a 20 kWe Closed Brayton Cycle system for an initial lunar outpost connecting multiple modular units to a single reactor for lunar bases, and the eventual deployment of multi-megawatt systems for lunar colonies is discussed. System performance and mass details were generated by an author developed code (BRMAPS) including options for increased power output by artificially depressing lunar daytime sink temperatures and maximum power generation during the lunar night.

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